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Chapter 7

Gasification of Municipal Solid Waste

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Abstract

Gasification of municipal solid waste (MSW) is an attractive alternative fuel production process for the treatment of solid waste as it has several potential benefits over traditional combustion of MSW. Syngas produced from the gasification of MSW can be utilized as a gas fuel being combusted in a conventional burner or in a gas engine to utilize the heat or produce electricity. Also, it can be used as a building block for producing valuable products such as chemicals and other forms of fuel energy. This book chapter covers the properties of MSW, gasification mechanism, chemistry, operating conditions, gasification technologies, processes, recovery system, and most importantly by reviewing the environmental impacts of MSW gasification. As one of recent advanced technologies, a case study of pilot-scale MSW gasification is introduced, which could be one of the most efficient pathways to utilize the technology to produce electricity with a newly developed gasification process by reducing tar and pollutant emission.

Keywords: municipal solid waste, gasification, waste to energy

1. Introduction

Gasification of municipal solid waste (MSW) is an attractive alternative fuel production process for the treatment of solid waste as it has several potential benefits over traditional combustion of MSW. The so-called "syngas" obtained by gasification has several applications. It can be utilized as a gas fuel being combusted in a conventional burner or in a gas engine and then connected to a boiler and a steam turbine or gas turbine to utilize the heat or produce electricity. Also, it can be used as a building block for producing valuable products such as chemicals and other forms of fuel energy, as discussed in the following literature review [1]. This reference, called *Waste to Energy Conversion Technology*, introduces the theory behind gasification and pyrolysis and outlines the key differences between them and conventional combustion in Chapter 9, "Gasification and pyrolysis of MSW." This chapter also provides an overview of the types of products that can be made from gasification, and the applications of these products are presented. In addition, different types of gasification processes are addressed. However, it fails to discuss the properties of MSW, also gasification principles were not described in details into the chapter. Most importantly, environmental impacts of MSW gasification were not addressed in the chapter. Therefore, an up-to-date book chapter on gasification of MSW was much needed. To address this issue, an initiative was taken to write a book chapter on MSW gasification by assessing the present contents of MSW gasification by covering the properties of MSW, gasification mechanism, chemistry, operating conditions, gasification technologies, processes, recovery system, and most importantly by reviewing the environmental impacts of MSW gasification. The properties of MSW are discussed in Section 2. In Section 3, we discuss gasification principles such as the mechanism, chemistry (reactions), and operating parameters (equivalent ratio, temperature, residence time, cold gas efficiency, carbon conversion efficiency, tar content, etc.). Section 4 shows the MSW gasification technologies and processes, including plasma gasification, fixed-bed gasification, fluidized gasification, and worldwide plants of various types. Sections 5 and 6 describe energy recovery systems and environmental impacts of MSW gasification by reviewing available literatures and some case studies in recent practices and developments. Finally, a case study of a pilot-scale MSW gasification is introduced, which could be one of the most efficient pathways to utilize the technology to produce electricity with a newly developed gasification process with reducing tar and pollutant emission in Korea.

2. MSW properties

The design of a process for the management of MSW and the results for the economic evaluation and development of a feasible business plan require an introduction of the properties of MSW. Therefore, these are presented to support those who are performing such design and economic evaluations [2]. **Table 1** shows the density of various components such as some typical properties of the MSW of interest. **Table 1** also illustrates the typical moisture content with range for some specific properties of the MSW of interest. The typical values of elemental analysis and proximate analysis for some material of interest in MSW are also shown in **Table 1**. In the case of elemental analysis values for carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulfur (S), and ash; and in the case of proximate analysis values for moisture, volatiles, fixed carbon, and ash are shown on a percentage of weight basis [3].

Another important factor for evaluating and designing the process of MSW is calorific value of the appeared materials. **Table 2** shows some standard calorific value of various materials generally found in MSW [5].

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Typical properties of uncompacted wastes (USA Data)-density					
	Density (kg/m^3)				
Food wastes	288				
Paper	81.7				
Plastics	64				
Garden trimmings	104				
Glass	194				
Ferrous metal	320				
Typical moisture contents of wastes					
	Moisture content (wt.%)				
Residential	**Range**	**Typical**			
Food wastes (mixed)	50–80	70			
Paper	4–10	6			
Plastics	1–4	2			
Yard wastes	30–80	60			
Glass	1–4	2			
Typical proximate analysis values (% by weight)					
Type of waste	**Moisture**	**Volatiles**	**Carbon**	**Ash**	
Mixed food	70.0	21.4	3.6	5.0	
Mixed paper	10.2	75.9	8.4	5.4	
Mixed plastics	0.2	95.8	2.0	2.0	
Yard wastes	60.0	30.0	9.5	0.5	
Glass	2.0	—	—	96–99	
Residential MSW	21.0	52.0	7.0	20.0	
Typical elemental analysis (% by weight):					
Type of waste	**C**	**H**	**O**	**N**	**S**	**Ash**
Mixed food	73.0	11.5	14.8	0.4	0.1	0.2
Mixed paper	43.3	5.8	44.3	0.3	0.2	6.0
Mixed plastics	60.0	7.2	22.8	—	—	10.0
Yard wastes	46.0	6.0	38.0	3.4	0.3	6.3
Refuse derived fuel	44.7	6.2	38.4	0.7	<0.1	9.9

Table 1. Physical properties of MSW [4].

Material	Calorific value (BTU/lb)	Ash content (wt.%)	Moisture content (wt.%)
Soft wood	6330	0.1	19
Fiberboard, 90% paper	7600	4.6	7.5
Damp wood	5690	1.2	27.5
Leather trimmings	7670	5.2	10.4
Cotton seed hulls	10,600	2.47	8.9
Sludge material (steel mill)	9150	24.5	1.9
Nitrile rubber	15,240	3.4	
Cardboard, granulated	8592	12.3	6.4
Carbon residue	13,681	8.7	0.0
Wood waste, sawdust	7500	0.8	14
Nut shells	7980	1.75	11.85

Table 2. Calorific values of various materials [4].

3. Basics of gasification

3.1. Mechanism

Combustion, gasification, and pyrolysis are thermal energy conversion processes available for the thermal treatment of solid wastes. **Figure 1** introduces all the potential pathways to convert MSW or biomass into different energy forms using thermal, mechanical, and biological processes. **Figure 2** shows the schematic diagram of syngas production and how to utilize the gas for various purposes such as power generation, creating chemicals by upgrading steps, and further biochemical processing before producing fuels or chemicals. As shown in these figures, different products are obtained from the application of these processes, and different energy and residual material recovery systems can be used in various types of technologies.

Gasification is a thermochemical conversion process of carbonaceous materials into gaseous product at high temperatures with the aid of gasification agent. The gasification agent (another gaseous compound) allows the feedstock to be quickly converted into gas by means of different heterogeneous reactions [6–9]. The gaseous product obtained during this process is called synthetic gas (syngas) or producer gas, and it mainly contains hydrogen, carbon monoxide, carbon dioxide, and methane. Also, a small amount of inert gases, hydrocarbons, tar, and gas pollutants can be found [10]. Based on the effect of gasification agent, gasification can be divided into two categories. If the gasification agent partially oxidizes the feed material it is called direct gasification. During direct gasification, to maintain the temperature of the process, oxidation reaction supplies the required energy. If the gasification process takes place without the aid of gasification agent it is called indirect gasification [7, 11]. Usually steam is used for indirect gasification as it is easily available. Moreover, it increases the hydrogen content in the producer gas [7].

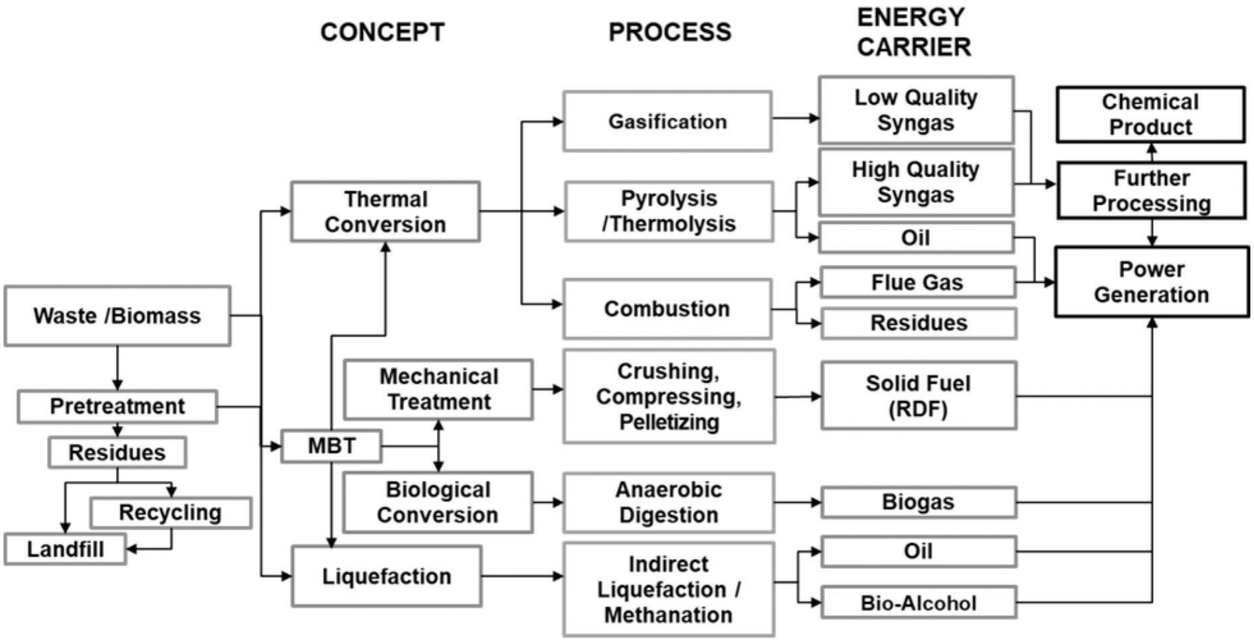

Figure 1. Pathways to convert MSW to different types of energy forms or chemicals through various conversion processes.

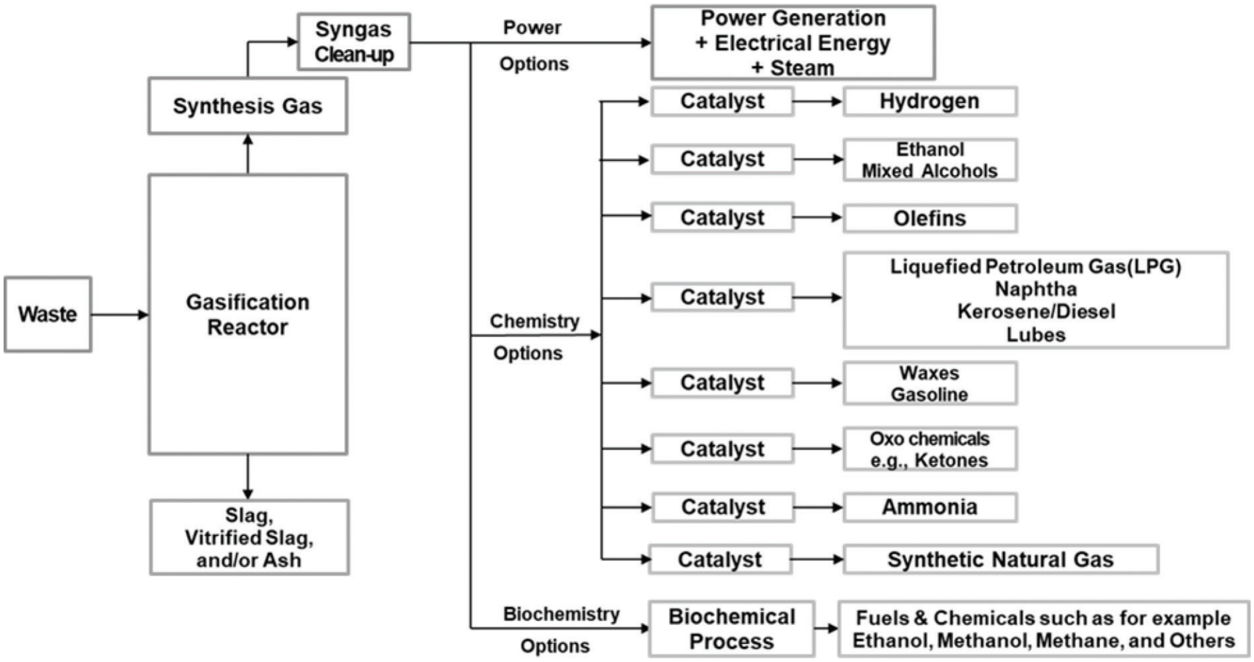

Figure 2. Pathway of waste to energy (gases, fuels, chemicals) by gasification.

As shown in **Figure 3**, two main gasification processes can be classified into direct and indirect gasification processes. Indirect gasification processes are conducted without air or oxygen injection. The heating value of the syngas is significantly affected by the presence of nitrogen. In the absence of nitrogen in indirect gasification process, the volumetric efficiency and higher heating value of producer gas both increases [12, 13]. Also, indirect gasification

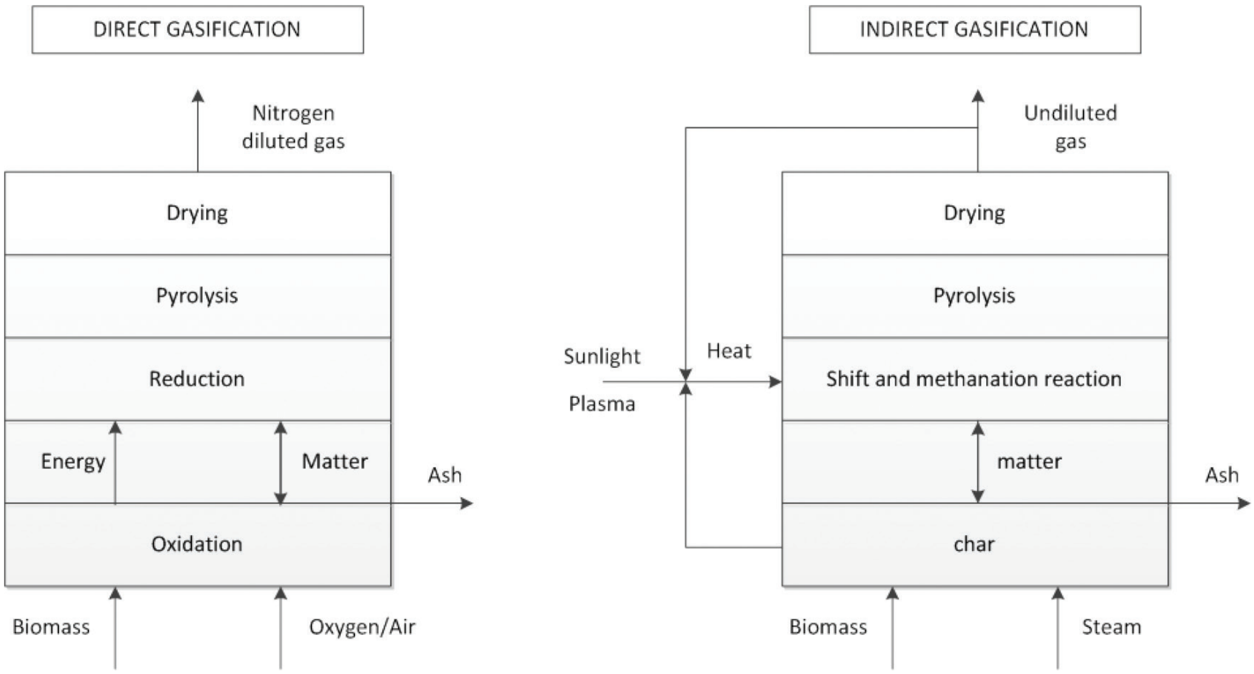

Figure 3. Direct and indirect gasification processes.

process decreases the cost of gas clean up and energy recovery by lowering the gas production rate. However, the process is quite complex and the investment cost is higher [7].

Pure oxygen gasification as direct gasification has same advantages over indirect gasification. However, the cost of producing pure oxygen is expected to account for more than 20% of the total cost of electricity production [14].

Generally, a gasification system is composed of three stages: (1) gasifier for useful producing syngas; (2) the syngas cleaning system for removal of pollutants and harmful compounds; (3) an energy recovery system such as a gas engine. Additionally, sub-systems are included to prevent environmental impacts such as air pollution, solid wastes, and wastewater.

3.2. Chemistry

3.2.1. Process steps

The gasification process of solid waste has endothermic and exothermic reactions, which are successive and repetitive [15, 16]. **Figure 4** describes the main reactants and steps of the gasification process.

• Heating and drying at about 160°C: In this stage, the moisture and steam from the feedstock are removed by the porous solid phase.

• Devolatilization (or pyrolysis or thermal decomposition) at about 700°C: This stage determines the thermal cracking reactions and conversion of heat and mass, including light permanent gases (such as H_2, CO, CO_2, CH_4, H_2O, and NH_3), tar (condensable hydrocarbon vapors), and char (residue emitted after devolatilization). Vapors produced in this stage undergo thermal cracking to gas and char. In the case of MSW, as described in **Figure 4**, high contents

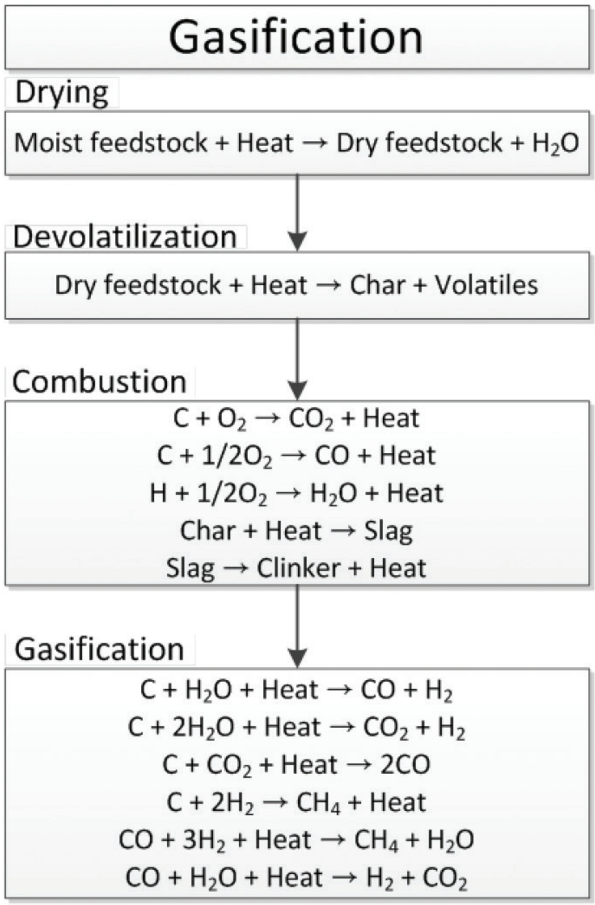

Figure 4. Main reactions and steps of gasification process.

of carbon and hydrogen, which are easily converted to combustible gases in volatiles, are included in the feedstock. The quantities, composition, and characteristics of chemical species released due to devolatilization are dependent on several factors such as original composition and structure of the waste, temperature, pressure, and heating rate imposed by particular reactor types. In devolatilization, various gas compositions are produced, and these gases are generated by the hydrogen and carbon in the waste [16, 17].

• Many chemical reactions occur in a reducing environment that is in remarkably lower oxidation (25–50%) than stoichiometric oxidation. Following **Table 3**, in an auto-thermal gasification process, the partial oxidation of combustible gas, vapors, and char are controlled by the amount of air, oxygen, or oxygen-enriched air. Also, this heat is necessary for the thermal cracking of tar hydrocarbons and char gasification by steam, and carbon dioxide maintains the operation temperature of the gasifier. Following the enthalpy of reactions 1, 2, and 3 in **Table 3**, in auto-thermal gasification processes, about 28% of the carbon heating value is invested in CO production, and the remaining 72% of the carbon heating value is conserved in the gas. The heating value of gas is generally between 75 and 88% of the original fuel because it also contains some hydrogen. If this value were 50% or lower, gasification using coal, biomass, and waste would probably never have become such an interesting process [18]. On the other hand, in an allo-thermal gasification process, the heat is supplied by external sources that are using heated bed materials, burning chars or gases, and utilizing plasma touch. The specific

tars, nitrogen and sulfur oxides, dioxins and furans, and particle materials. Various strategies can be adopted to control exhaust gas in the gasification process, and, as mentioned above, they are rigorously dependent on the adopted plant configurations, especially regarding the particular requirements of the specific energy conversion device. In any case, an obvious advantage in that air pollution control is possible not only at the reactor outlet but also at the exhaust gas outlet through a variety of approaches. Furthermore, the low levels of oxygen (ER ranges between 0.25 and 0.50) in the gasification process strongly inhibit the formation of dioxins and furans even though hydrogen chloride in the syngas must be managed if combustion for heat or power follows gasification. Recently collected emissions data indicate that gasification technology meets emission standards [52]. A synthesis of these data is shown in **Table 6**, together with the limits of the European Community and Japanese standards.

6.2. Solid residue treatment

It is important to report some considerations regarding the management of solid residues such as bottom ash and air pollution control (APC) residues to define the environmental performance of gasification-based WTE facilities. Depending on the type of waste and on the specific gasification technology, the type and composition of these residues differ greatly [22, 51, 53, 58]. **Table 7** reports some leaching tests carried out on the slags of two large-scale, high-temperature gasification units. All values are significantly lower than the emission standard, and the low impurity content of the slag and its good homogeneity make it possible to sell for a variety of uses such as aggregates in asphalt pavement mixtures. The metals recovered from the melting section can be also recovered during the chemical treatment of fly ash and then landfilled.

Company, plant location	**Nippon Steel Kazusa, Japan**	**Thermoselect Nagasaki, Japan**	**Ebara TwinRec Kawaguchi, Japan**	**Mitsui R21 Toyohashi, Japan**	**Energos Averoy, Norway**	**Plasco En. Ottawa, Canada**	**EC/ Japanese Standard**	**Korea Standard**
Waste capacity	200 tons/day	300 tons/day	420 tons/day	400 tons/day	400 tons/day	100 tons/day		
Power production	2.3 MWe	8 MWe	5.5 MWe	8.7 MWe	10.2 MWe	—		
Emission, mg/m^3_N(at 11% O_2)								
Particulate	10.1	< 3.4	< 1	< 0.71	0.24	9.1	10/11	14.2
HCl	< 8.9	8.3	< 2	39.9	3.61	2.2	10/90	16.7
NOx	22.3	—	29	59.1	42	107	200/229	106.8
SOx	< 15.6	—	< 2.9	18.5	19.8	19	50/161	85.5
Hg	—	—	< 0.005	—	0.0026	0.0001	0.03/–	0.09
Dioxins/ furans, n-TEQ/m^3_N	0.032	0.018	0.000051	0.0032	0.0008	0.006	0.1/0.1	—

Table 6. Some certified emissions from waste gasification plants [30, 48, 52, 54–57].

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Element (mg/L)	Regulation[a]	Measured[b]	Measured[c]	Korea standard[d]
Cd	< 0.01	< 0.001	< 0.001	< 0.03
Pb	< 0.01	< 0.005	< 0.005	< 0.1
Cr^{6+}	< 0.05	< 0.02	< 0.02	< 0.05
As	< 0.01	< 0.001	< 0.005	< 0.05
T-Hg	< 0.0005	< 0.0005	< 0.0005	< 0.001
Se	< 0.01	< 0.001	< 0.002	—
F	< 0.8	—	< 0.08	—
B	< 1.0	—	< 0.01	—

[a]Quality standard for soil (in agreement with Notification No. 46, Japanese Ministry of the Environment and the JIS-Japanese Industrial Standard K0058).

[b]Tests carried out in a Nippon Steel high-temperature shaft furnace with a capacity of 252 tons/day of MSW, bottom ash from other MSW incinerators, and residues from recycling centers [59].

[c]Tests carried out in a JFE high-temperature shaft furnace plant having a capacity of 314 tons/day of RDF from MSW [32].

[d]Recycling standard of waste (No. 5 of enforcement regulations in waste management law in Korea).

Table 7. Results of some slag leaching tests in two high-temperature MSW gasifiers [30].

Therefore, it can be deduced that the amount of solid residues generated in the MSW gasification process is reduced and the throughput at the landfill can be reduced.

6.3. Wastewater treatment

In the gasification process, wastewater produced by the gas cooler and the wet scrubber containing many soluble and insoluble pollutants such as acetic acid, sulfur, phenol, and other organic compounds [10]. The insoluble matter in this wastewater is mainly composed of tar. The amount of wastewater generated by removing tar through the scrubber is about 0.5 kg/Nm^3 of treated gas [60], and requires expensive treatment. There are also some minor problems such as high salt content and low pH associated with the wastewater generated in gasification process. However, these can be controlled easily by doing chemical precipitation and neutralization [61].

"In the gasification plant Thermie Energy Farm, one of the three IGCC projects selected for funding by the European Union, the sequence of treatment for tar-rich wastewater is: (a) precipitation of sulfur by iron sulfate addition; (b) recovery of sulfur and dust by filtering; (c) disposal of filter cake; (d) stripping off gases and the major part of the hydrocarbons dissolved in the water; (e) partial evaporation of water and usage of condensate as scrubber make-up; and (f) discharge of evaporator blowdown to conventional bio-treatment" [60, 62].

The recovered salts are treated through sanitary landfills because their potential for contamination is very low. The hydrocarbons and the recovered gas are decomposed and recovered as energy in the combustor [60, 62]. Recent trends due to difficulties in treatment and disposal are developing tar-free gasification technologies, but this is nonetheless possible only for wastes with low contaminant content [10].

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